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# PLASTIC BEHAVIOR OF POLYCRYSTALLINE TANTALUM IN THE $5 \times 10^7$/s REGIME

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**Abstract.** The goal of this experiment is to investigate the plastic response of Tantalum to dynamic loading at high strain rates. The samples used were derived from high purity rolled plate, polished down to thicknesses in the range 25-100 $\mu$m. Dynamic loading was applied by direct laser ablation of the sample, with pulses up to 10 ns long, at the Jupiter Laser Facility. The elastic-plastic wave structure was measured using two line VISAR systems of different sensitivity, and strain rates were inferred from the rise time of the waves. The elastic wave amplitudes indicated flow stresses between 2 and 3 GPa, depending on the sample thickness. Samples were recovered for post-shot metallographic analysis.
**Keywords:** shock, plasticity
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## INTRODUCTION

Ta has been studied extensively as a prototype strong bcc material with high melting point, and for its use in munitions. The dynamic strength of Ta is of particular interest because of its time dependence, motivating the development of multi-scale strength models based on *ab initio* dislocation dynamics [1].

Numerous previous experiments have investigated the strength behavior using different loading conditions and measurement techniques, mostly with shocks but also a few ramp loading studies. Mock and Holt [2] performed impact experiments around 2.5 GPa with samples 3.73 mm thick of $>$ 99% purity, and inferred a yield stress of 1.05 GPa using capacitive displacement gauges. Furnish et al [3] performed impact experiments from 3.5 to 12 GPa with samples 5.0 and 7.3 mm thick, and inferred a yield stress of 0.95 GPa using laser Doppler velocimetry. Gray et al [4] performed impact exper-

iments on commercially pure cross-rolled material from 2.5 to 12 GPa, and inferred a yield stress around 0.5-0.6 GPa using manganin gauges 2 mm from the impact surface. Swift et al [5] performed ablative shock experiments on rolled foils $>$ 99.8% pure and 25-70 $\mu$m thick, inferring a yield stress of around 1.6 GPa using laser Doppler velocimetry. Reed et al [6] performed impact experiments on commercially pure cross-rolled material 1-3 mm thick from 10 to 50 GPa, inferring yield stresses 1.0-1.5 GPa (decreasing with thickness) using laser displacement interferometry. Eggert et al [7] performed electromagnetic ramp loading experiments on commerially pure cross-rolled samples 400-700 $\mu$m thick, and inferred yield stresses around 1.0 GPa using laser Doppler velocimetry. Eggert et al [8] performed ablative ramp loading experiments on sputtered samples 12-20 $\mu$m thick, and inferred flow stresses of 2-3 GPa using laser Doppler velocimetry.

It is difficult to draw firm conclusions on the systematic behavior of Ta across wide ranges of strain rate from existing data, because of differences in microstructure. It is highly desirable to obtain data on

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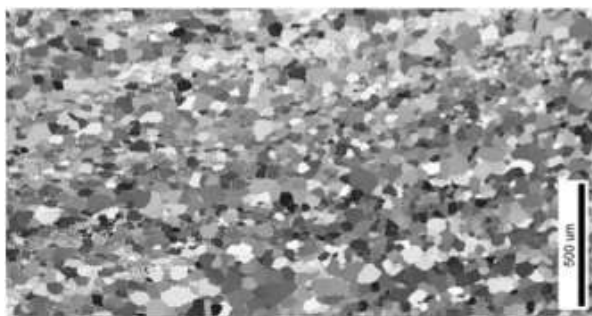[1] Current address: University of Nevada, Reno, Nevada 89512, U.S.A.

**FIGURE 1.** Microstructure of Ta used (from electron backscatter diffraction scan).



**FIGURE 2.** Schematic of experimental configuration.

flow stress at high strain rates and for thin samples, but Ta has been notoriously difficult to thin down from the bulk stock used to prepare thick samples, particularly below 100] $\mu$m, because internal stresses cause 'potato chip' deformations.

Here we describe the results of ablatie loading experiments on samples 25-100 $\mu$m thick, successfully thinned down from bulk material. Beside providing yield stress data in their own right, these experiments were intended to calibrate the applied loading history for studies of decaying shocks in which a relatively thick ($\sim$ 1 mm) sample was recovered for metallographic analysis [9].

## SAMPLE PREPARATION

Samples were prepared by grinding and polishing from bulk cross-rolled pressings. The texture of the source plates comprised $< 100 > / < 111 >$ banded structures with a grain size of around 50 $\mu$m (Fig. 1). Potato-chipping was avoided by using a double sided polish with the samples glued firmly to the substrate. In this way, it was possible to prepare flat samples to a thickness of less than 25 $\mu$m. For these experiments, samples were prepared of thickness around 25, 50, and 100 $\mu$m.

## EXPERIMENTS

Dynamic loading was induced by laser ablation of one side of the sample, at the Jupiter Laser Facility at Lawrence Livermore National Laboratory (Fig. 2), operating at 527 nm. A phase plate was used to dis-
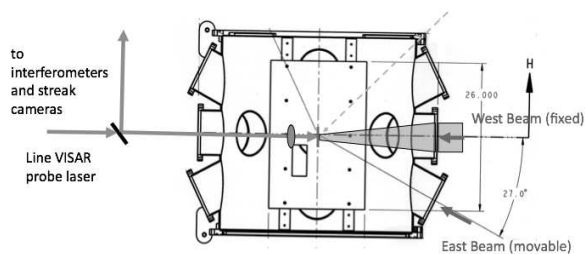
tribute the laser energy uniformly over a square spot of side 1.3 mm (Fig. 3). An equivalent focal plate system was used to permit the drive beam to be aligned and focused under vacuum before each shot, using a remotely-moved mirror to direct the alignment beam onto a CCD camera. The laser pulse was 10 ns long, with temporal shape chosen to induce a shock of approximately constant pressure or a pressure ramp. Laser Doppler velocimetry of the 'VISAR' type [10] was used to measure the velocity history across a line approximately 1 mm wide on the free surface of each sample opposite the ablated surface, the signal being split between interferometers of two different velocity sensitivities to avoid ambiguities from jumps in the interference fringes. The VISAR system used a pulsed probe laser operating at 532 nm, with pulses 40 ns long. The line-imaged interference fringes were recorded using optical streak cameras. We have used this experimental configuration in numerous previous experiments [11, 12, 5], but this is the longest temporally shaped laser pulse reported so far for direct ablation of the target.

In order to induce a constant ablation pressure in Ta, the laser irradiance should be increased by several tens of percent during a pulse of this length. In practice, it was difficult to generate the precise shapes desired to induce constant pressures beyond about 7 ns, so the shock pressures generally decayed somewhat during the pulse. This decay also affected the ramp experiment, in which it was intended to apply a ramp for 7 ns followed by a sustained pressure for 3 ns; in practice the irradiance and thus the pressure decreased after 7 ns. (Fig. 4.)

Fifteen experiments were performed, of which one used a pressure ramp. A further five experiments were performed on thick ($\sim$ 1 mm) samples with the drive pulse repeated as accurately as possible so as to use the velocity record from the preceding thin sam-
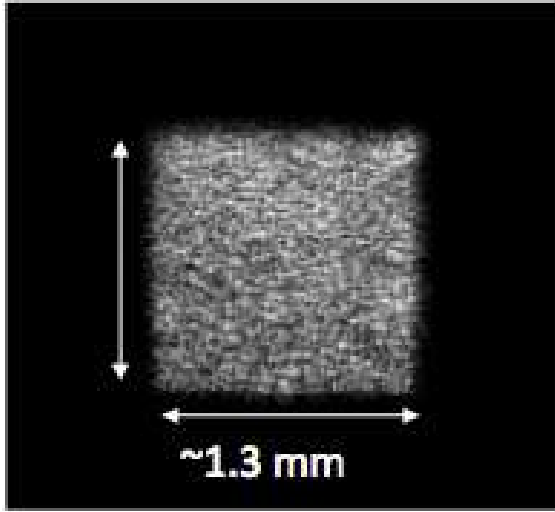
**FIGURE 3.** Equivalent focal plane image of drive spot using phase plate.
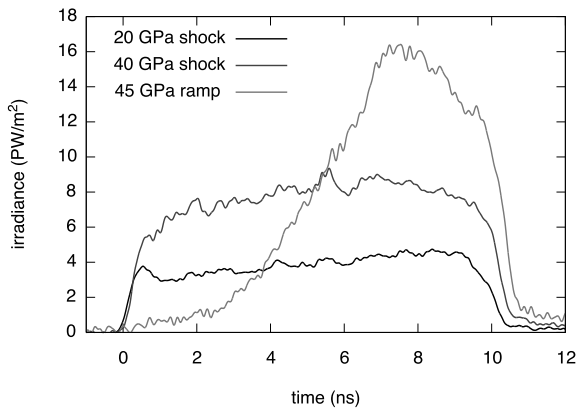


**FIGURE 4.** Example laser pulse shapes.

ple to calibrate the drive. The drive pressure varied between 15 and 60 GPa. Velocimetry data were obtained from all shots, though records from one of the interferometers was lost on a few shots because of a triggering problem. Elastic waves were evident for shock pressures up to at least 40 GPa, but were relatively hard to distinguish for shock pressures above 30 GPa. Experiments of similar thickness and pressure produced similar velocity histories, demonstrating repeatability of the experiments.

The streak cameras had a limited time window,

and the priority was to capture the elastic wave and peak of the shock. It was also desirable to start the recording window before the start of the laser pulse, in case of early motion which might indicate a laser prepulse or preheat induced by x-rays or electrons (none of which was observed). Deceleration following the shock peak was observed on all experiments, but the re-acceleration following tensile damage was only captured on a few shots. These data allowed a spall strength to be estimated from the magnitude of the pullback.

Relative timing of the streak records and the drive pulse was established by performing timing measurements in which a small amount of energy from the drive laser was directed through the VISAR optics to the cameras. An electronically triggered optical fiducial pulse was directed to the edge of each streak camera, and the relative timing established between the drive laser and the fiducial laser. The fiducial pulse was recorded on every shot. If any jitter occurs in the signal between the front end of the drive laser and the target area, this would not show up as a change in the position of the fiducial pulse on the streak record. There was evidence of such jitter on some experiments. A more robust approach is to take a small amount of light from the drive beam, e.g. leakage through a mirror, and convey it optically to the streak cameras.

## RESULTS

The amplitude of the elastic wave was around 230 m/s in samples around 25 $\mu$m thick, falling to around 200 m/s in samples around 50 $\mu$m thick, and to around 140 m/s in samples 107 $\mu$m thick. There was little dependence on the peak pressure, and the ramp loaded sample 107 $\mu$m thick had much the same precursor as did shocks to 20 and 40 GPa. Strain rates were estimated from the rise of the elastic wave to be around $10^7$/s for the ramp, and $5 \times 10^7$/s for the shocks. The elastic wave structure was brought out more clearly by plotting the surface velocity as a function of scaled time $\tilde{t} \equiv t/l$ where $l$ is the sample thickness. (Figs 5 and 6.)

A range of spall strengths was obtained, from 8.5 to 11.5 GPa. The spall strength correlated well (varied monotonically) with the peak shock pressure, and not with sample thickness or strain rate (Fig. 7).
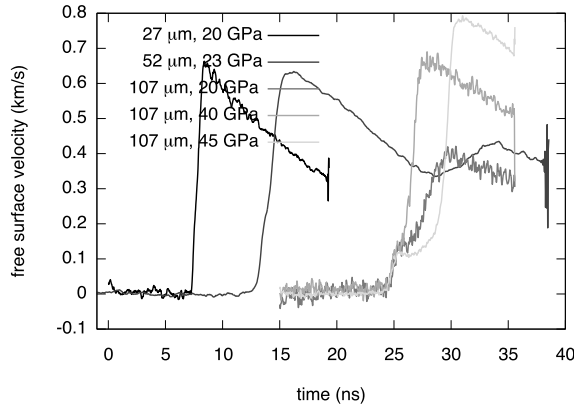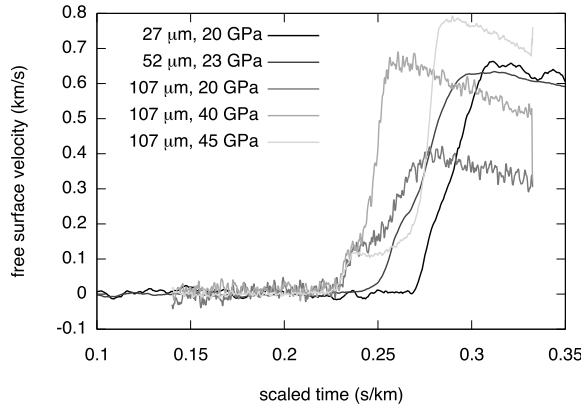
**FIGURE 5.** Example surface velocity histories.



**FIGURE 6.** Surface velocity histories, plotted against scaled time.

## CONCLUSIONS

Thin ($< 25\,\mu$m) samples of Ta, flat enough for dynamic loading experiments, can be obtained from bulk stock by careful polishing. For strain rates $\sim 10^7$/s, Ta exhibits yield stress $\sim 2$ GPa in samples $100\,\mu$m thick, insensitive to loading history. Rises to 3.5 GPa in samples 25 and $50\,\mu$m thick. In this regime, yield stress seems relatively insensitive to texture and purity: results are consistent with Omega data on sputtered deposits and Trident data on rolled foils. Apparent spall strengths were $\sim$8-11 GPa, increasing with peak shock pressure. The surface velocity measurements were used to assess loading his-



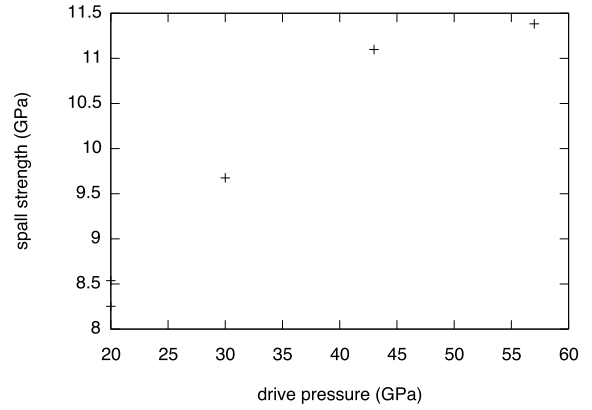**FIGURE 7.** Estimated spall strength.

tory vs position in thick ($\sim$mm) samples.

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